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Water Injected Turbomachinery

R.C. Hendricks
Glenn Research Center, Cleveland, Ohio

D.T. Shouse and W.M. Roquemore
Wright Patterson Air Force Base, Dayton, Ohio

March 2005

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R.C. Hendricks
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

D.T. Shouse and W.M. Roquemore
Wright Patterson Air Force Base
Dayton, Ohio 45433

ABSTRACT

From antiquity, water has been a source of cooling, lubrication and power for energy transfer devices. More recent applications in gas turbines demonstrate an added facet, emissions control. Fogging gas turbine inlets or direct injection of water into gas turbine combustors, decreases NO_x and increases power. Herein we demonstrate that injection of water into the air upstream of the combustor reduces NO_x by factors up to three in a natural gas fueled Trapped Vortex Combustor (TVC) and up to two in a liquid JP-8 fueled (TVC) for a range in water/fuel and fuel/air ratios.

INTRODUCTION

Industrial Applications

Turbomachines

Water injected industrial gas turbine combustors have been operational for many years. More recently, inlet fogging has provided enhanced efficiency with decreased emissions and lower costs. Peterson (2003) gives an example; dropping the compressor inlet air temperature 11 °C (20 °F) of a 100 MW facility, by fogging the inlet, produces nearly a 10 percent increase in power. In terms of this additional power, overall turbine efficiency is increased 3 percent with 30 percent less fuel, 20 percent less CO_2 and 10 percent less total NO_x. Capital costs of a new plant are $750/kW as compared to $20/kW for an inlet fogging system that can be installed in 3 months compared to 3 years for a new plant [Peterson (2003)]. Further, Mee (1999) cites the GE-7EA turbine as normally steam injected and evaporatively cooled producing about 140 ppm NO_x. With inlet fogging an additional 18 percent reduction in NO_x was noted by Mee (1999).

Controlled fogging of the industrial gas turbine inlet moves the hot day operating point of the engine back to its peak efficiency point enabling it to continually operate in the specific fuel consumption (SFC) bucket. An aero engine is designed for cruise conditions and operates outside the SFC bucket during takeoff, so inlet fogging would not have much effect on efficiency, yet may decrease surge margin [Horlock (2001)], an undesirable effect.

These industrial levels of improvement may not be entirely realized in aero engines, yet the B-47 with six J47-GE-25A turbojets at 6 000 lbs of thrust (dry), or 7 200 lbs of thrust (using water injection for takeoff) provided a 20 percent increase in thrust (Boeing web site: http://www.aviation-history.com/boeing/b47.html). Water injection was commonly used during WWII to augment engine HP by 12 to 15 percent with similar examples in post WWII civil aviation piston aircraft (e.g., Martin 404). Still today, the B52-B powered by eight PW J-57-19 turbojet engines, each produce 12 000 lbs of thrust with water injection (NASA Dryden web site: http://www.dfrc.nasa.gov/Newsroom/FactSheets/PDF/FS-005-DFRC.pdf) and 12 100 lbs thrust with water/alcohol injection (March Field web site: http://www.marchfield.org/gb52d.htm). The B52H series uses turbofan engines at 17 000 lbs thrust providing sufficient power without water injection.

An additional benefit of fogging may be clean component fluid dynamics. Washing the high pressure compressor (HPC) of a high performance aero-engine (e.g., PW 4077 series) can enhance HPC-efficiency up to 0.8 percent while restoring as much as 8 °C exhaust temperature (EGT) margin. Such data are not reported for industrial gas turbines, yet it would be expected that similar performance gains would ensue. Still washing and fogging water quality requires monitoring as long term accumulative effects of pH margins and trace minerals may be a detriment, although fuel cleanliness has similar problems, requiring proper materials compatibility.

Diesel Systems

While water injection is known to be effective in piston engines, using aviation-gas, to prevent detonation and enhance power output; in use and development are water injection systems with emphasis on diesel engines. Also in development are emulsified fuel-water blends that reduce NO_x emissions by 1/5 to 1/3 and particulate matter by 1/2 to 2/3. Emulsified fuels have been used in terrestrial fleet trials and hold some promise for aero and industrial turbomachine applications. A bibliography is provided by Sutton (2001). Supercritical fuel-water mixtures data show even lower emissions (<2.5 ppmv NO_x and 5 ppmv CO), based on No. 2 fuel, yet require injection at significant pressure levels (e.g., above 220 bars) [Haldeman et al. (2002)].

Aero and industrial gas turbine system issues as maintenance, water quality, blade and coating life and reliability are beyond our scope, yet need to be addressed.

COMBUSTOR SYSTEMS DATA AND RESULTS

DOE-NETL Data and Results

HAT Data

As part of a humid air turbine (HAT) cycle program, tests were carried out in the low emissions combustor facility at DOE-NETL [Bhargava et al. (1999)]. At 1.38 MPa (200 psia) with side pilot fueling, NO_x increases about 1.5 ppm per 1 percent increase in fuel flow with CO nearly unaffected. With the addition of superheated steam mixed combustion-air, NO_x is reduced with a lessening of the dependency on equivalence ratio (fig. 1) [Bhargava et al. (1999)]. Yet too much steam (>20 percent) causes a narrowing and shifting of the kinetic-equilibrium-CO boundary and lean blow out (LBO) limit to higher equivalence ratios (fig. 2) [Bhargava et al. (1999)]. In terms of the cycle, the addition of 10 to 15 percent steam provides the largest return, lowering NO_x by factors of 3 to 8 depending on equivalent flame temperatures and higher reductions with equivalence ratio and piloting fuel injection.

For a given equilibrium temperature, 1620 °C (2950 °F), the dry-air equivalence ratio is 0.54 with NO_x at 15 ppm while at 15 percent steam, the humid-air equivalence ratio is 0.74 and NO_x at 3 ppm, indicating dry air is richer in free-O than humid air, yet the predominant NO_x formation is by the “Zeldovich” pathway [Bhargava et al. (1999)].

At constant flame temperature the NO_x increases, yet on the average, the ratio of NO_x with water injection/NO_x without water injection decreases exponentially with water/air mass fraction as shown in figure 3 for the data of Bharagava et al. (1999).

TVC Data

The NETL trapped vortex combustor (TVC) steam laden air data (Straub et al. (2002)) show a less dramatic decrease in NO_X with equivalence ratio, yet higher overall stability near LBO. In these tests the cavity φ_{cavity} was about 1.5 with the overall (main + cavity) $0.3 < \varphi_{overall} < 0.6$. The fuel rich TVC cavity “burns out” the CO with the excess oxygen rich air of the mains where the split is about 70 percent main, 30 percent cavity. For 10 percent

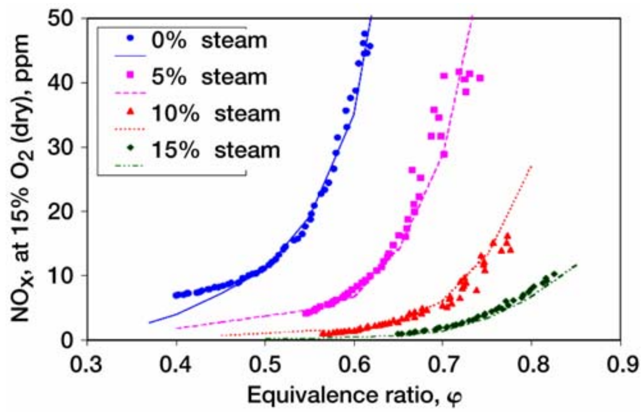


Figure 1.—Comparison between measured and computed NO_X for a 5% side pilot flame at 200 psi for different steam loading (Bhargava et al. Ref 8).

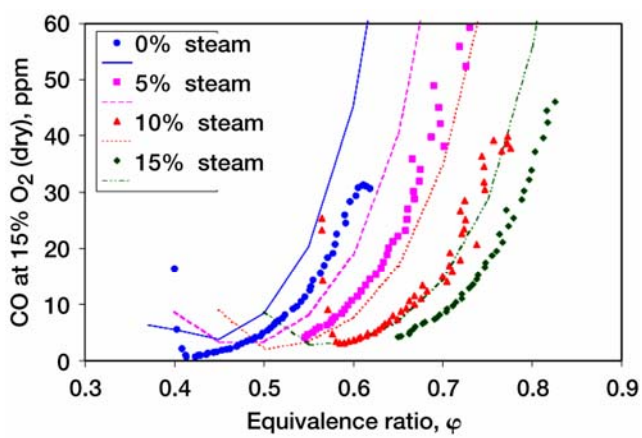


Figure 2.—Comparison between measured and computed CO for a 5% side pilot flame at 200 psi for different steam loading (Bhargava et al. Ref 8).

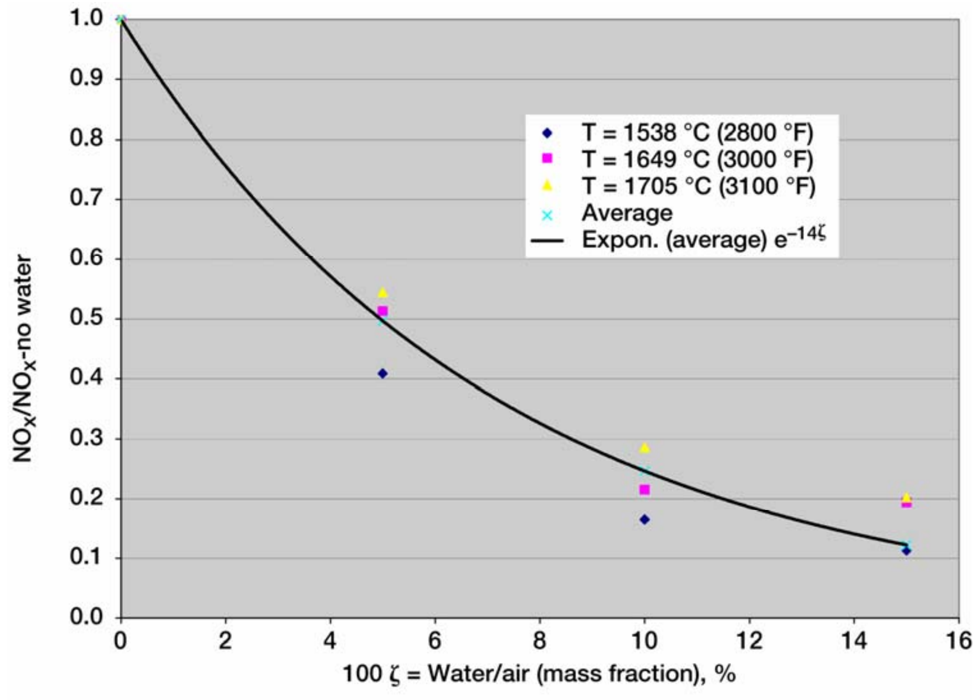


Figure 3.—NO_x reduction with water addition for constant flame temperature NETL-HAT (Bhargava et al. Ref 8).

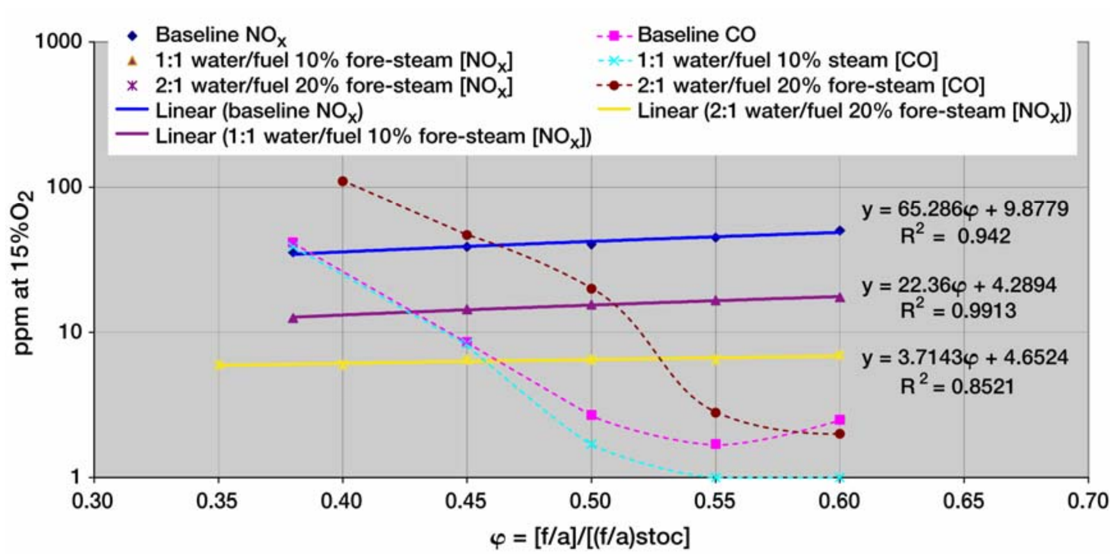


Figure 4.—NETL-Morgantown steam Injected TVC (Straub et al. Ref 9).

steam in the main flow, the NO_x production is nearly flat over a range $0.3 < \varphi_{overall} < 0.6$, with a reduction near 3.5 (fig. 4) and 5 with 20 percent steam addition. To more directly compare these reductions to those cited by (Bhargava et al. (1999)) one needs to look into the average flame temperatures.

Comparison of CO Emissions Data

The CO emissions data for both the HAT and TVC combustors are illustrated in figure 5. For the HAT system, the CO minimum shifts toward higher equivalence ratios as steam mass fraction increases. For the TVC system, there is little variation between no steam injection and

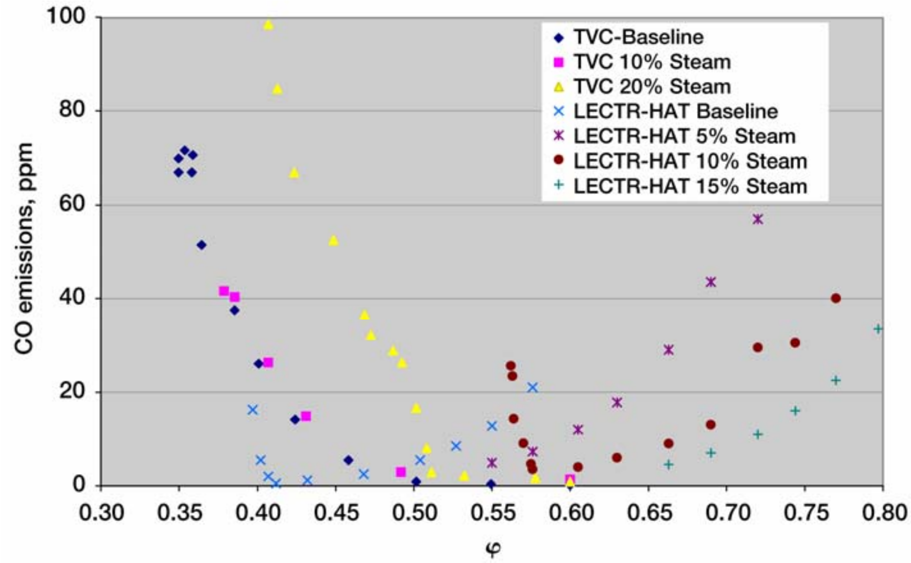


Figure 5.—NETL-TVC Straub, Ref 9 and NETL-LECTR (HAT-cycle) CO measurements (HAT-cycle read from graphs, Bhargava et al. Ref 8).

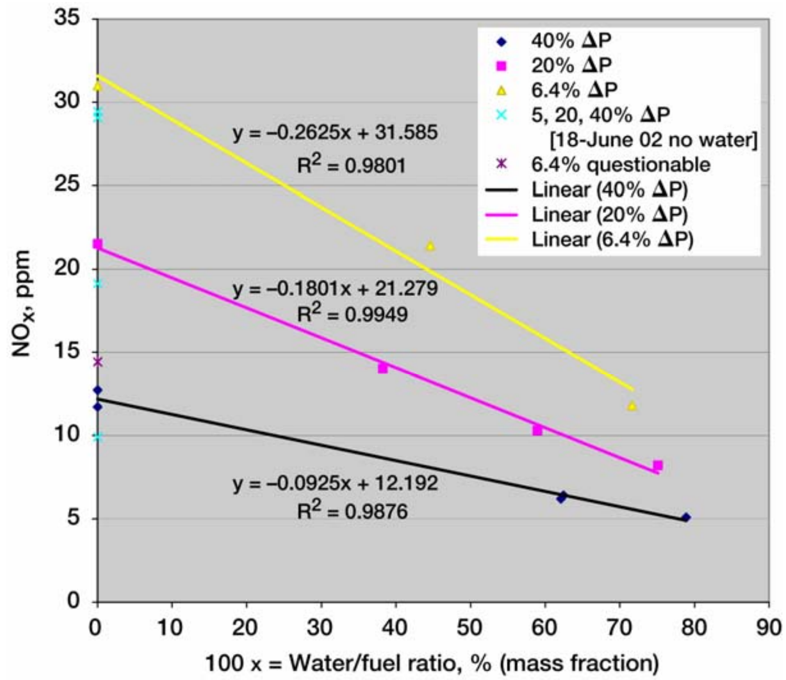


Figure 6.—HSTVC-NO_x reductions for water injected 4 in.-cavity only fueled lobe mixer combustor flow at 500 °F inlet temperature.

10 percent steam mass fraction injection with equivalence ratio. Yet at 20 percent steam mass fraction, there is a considerable shift toward higher equivalence ratio.

AFRL-WPAFB TVC Data

The NETL-TVC emissions data for natural gas fueling are in reasonably good agreement with the 4 inch Lobed TVC data taken at AFRL-WPAFB for JP-8 cavity only fueling and water (steam) injection over a range of combustor pressure drops from 6.5 to 41 percent. To a first order, for φ cavity only fueling of approximately 1.5, the reduction in NO_x is illustrated in figure 6 and follows the relation similar to that shown in figure 3.

$$NO_x \text{ with-water}/NO_x \text{ without-water} = \exp[-10\,\zeta]$$

where

$$\zeta = (w/a) = (w/f)\,(f/a) = (\text{water/fuel})\,(\text{fuel/air}) = (\text{water/air})_{(\text{mass basis})}$$

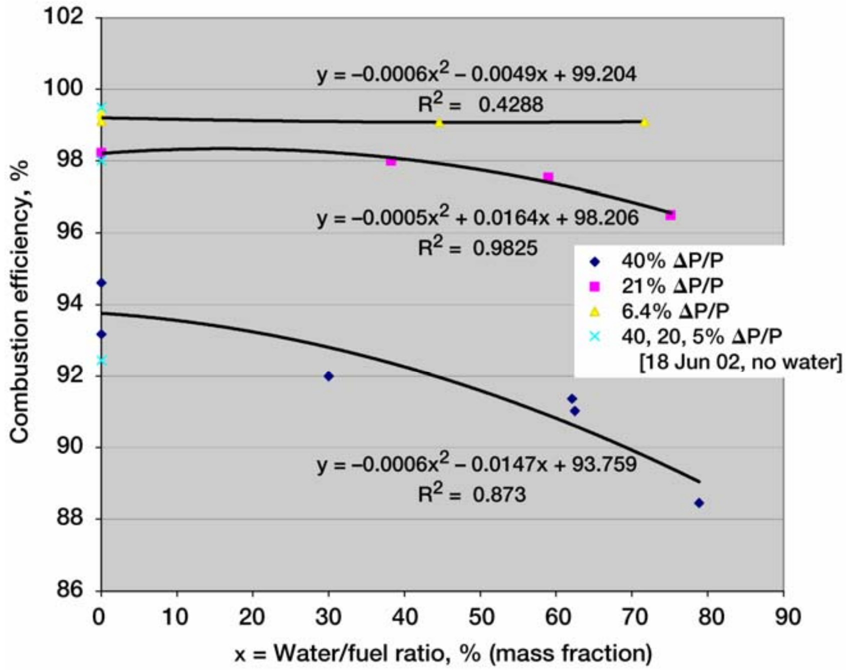


Figure 7.—HSTVC-10.2 cm (4 in.) cavity only fueled lobed mixer water injected combustor flow efficiencies for 260 °C (500 °F) inlet air/water.

A more representative formulation for the 4-in. TVC Cavity Only fueling Data (3 < percent combustor ΔP < 40)

NO_x = [0.005 × (%-Combustor ΔP) –0.29] × (weight flow water/weight flow fuel %) +
+ [34.2 – 0.55 × (%-Combustor ΔP)]
= a X + b

So the ratio of NO_x with water to NO_x without water is:

NO_x with-water/NO_x without-water = 1 + 100 (a/b) (w/f)
= 1 + 100 [0.5 (ΔP/P) – 0.29] (w/f)/[34.2 – 55 (ΔP/P)]

for $0.03 < \Delta P/P < 0.4$
$0 \le (w/f) < 1$

Under these conditions, the combustor performance changes little at low combustor pressure drops, yet losses are incurred as combustor Mach number increases to near 0.7 as illustrated in figure 7.

Emissions Modeling

In modeling NO_x emissions for gas turbine combustors, Huang (1975) provides "for convenience of the users" a linear relationship between specific humidity (ζ = mass water/mass dry-air) and NO_x, independent of fueling technique or equivalence ratio ($\zeta << 0.095$):

$$[NOx]_{humid\text{-}air} / [NO_x]_{dry\text{-}air} = 1.055 - 11\,\zeta$$

The relation underpredicts and overpredicts the NETL-HAT data which, on the average, for a mid-range in **φ** follows

$$\ln\,[[NO_x]_{humid\text{-}air}/[NO_x]_{dry\text{-}air}] = -28\,\zeta \quad 0.1 < \varphi < 0.62$$

with a more accurate representation given in terms of **φ.**

System Considerations

Water injection is very effective in reducing NO_x in gas turbine applications, yet a detriment may be the long term accumulative effects of pH margins and trace minerals (salts) (Dooley, Aschoff, and Pocock (1994)) although fuel cleanliness has similar problems. NO_x removal by water injection (based mostly on GE LM 2500 experience) costs between \$8000 to \$12000 per ton NO_x removed with a capital equipment cost nearly [\$60000 × (water flow rate, gpm)$^{1/2}$]. The increased maintenance for replacement of hot section components, water deionization and handling is not all that favorable, yet offered by most gas turbine manufacturers (Castaldini (1990)). Issues cited by Dooley et al. (1994) and Castaldini (1990), as system maintenance, water quality, blade and coating life and reliability, erosion and surge margin, are beyond our scope, yet need to be addressed in terms of current practice and in particular with inlet fogging.

CFD Study

CFD simulation of the Allied Signal ASE-40 3.25 MW industrial gas turbine combustor with comparisons to

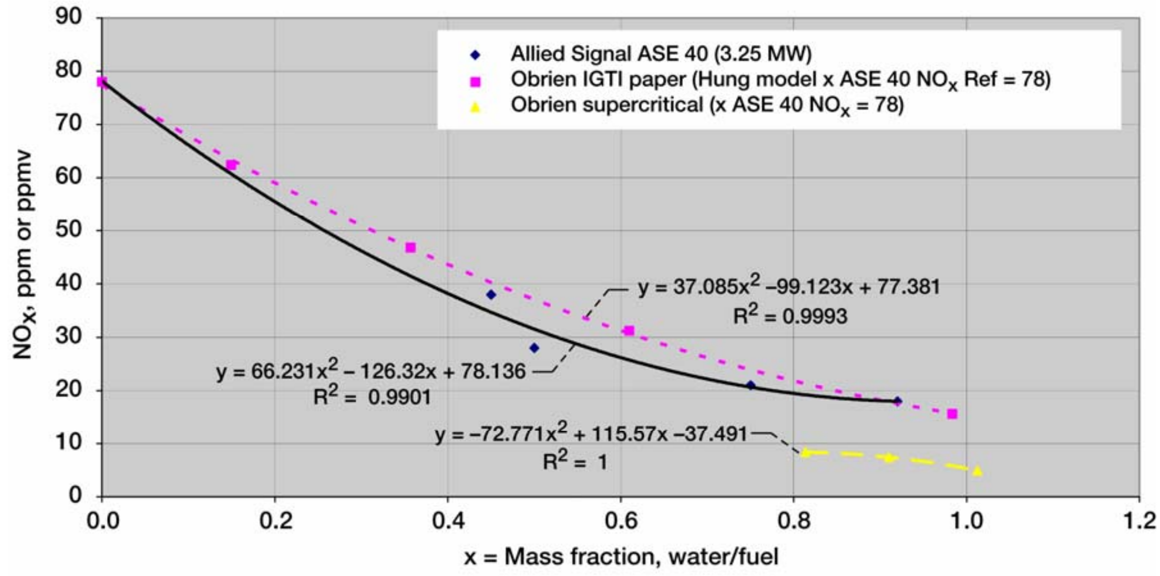


Figure 8.—NO_x emissions relative to Allied Signal ASE 40 3.25 MW class machine (Liever et al. Ref 14) (Obrien et al. Ref 15).

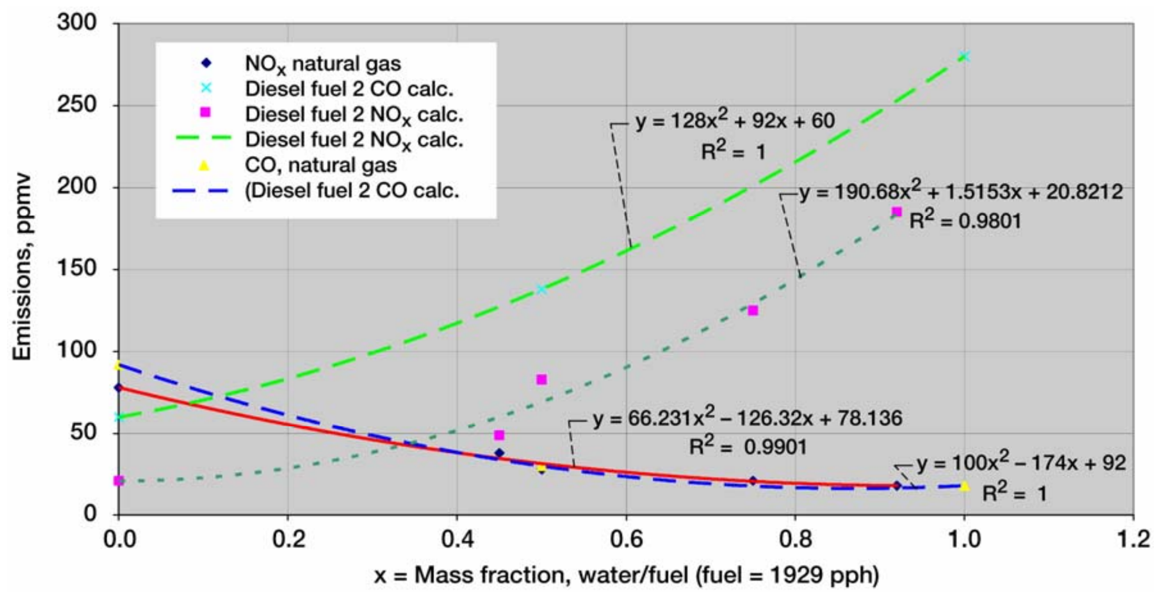


Figure 9.—Allied Signal ASE40 3.25 MW industrial gas turbine (Liever et al. Ref 14) (Obrien et al. Ref 15).

engine data are given by Liever et al. (1998). Several details regarding the natural gas/water atomization nozzle and the liquid (DF2 diesel) fuel/water injection nozzles along with CFD temperature and spray pattern predictions are reported. And most important, they compare their results with engine data (figs. 8 and 9). While the NO_x engine data are nearly double that predicted, the trends are correct and the CO rise is in good agreement as is the trend of decreasing average exit temperature with increasing water injection. At a water/natural-gas-fuel mass fraction of 0.9, the NO_{x_ζ}/NO_{x_0} or (NO_x/NO_x–no water) = 0.23, also predicted by Hung (1975), while $CO_\zeta/CO_0 = 9$. Other emissions (e.g., HC) are cited as increasing but not quantified. Based on the combustor air flow rate [11.66 kg/s (25.65 pps)], the water/air ratios (ζ) are less than 0.02, or less than 2 percent of the combustor flow is water (steam) [$\varphi_0 = 0.36$].[1]

[1]Marek gives EI (NO_x) = Mx/Ma [(1 + f/a)/f/a] × ppm(volume)/630 ≈ [(1+ f/a)/f/a] × ppm(volume)/630 where Mx = molecular weight of NO_x and Ma that of air. For GE-7EA machine, EI (NO_x) = (1+ 0.024)/0.024 × 140/630 = 9.5.

APPLICATIONS

Aero Applications

One thing to keep in mind about efficiency is that we may not see these levels of improvement in aero engines. The efficiency gains seen for industrial gas turbines are the result of being able to move the operating point of the engine on a hot day to back to its peak efficiency point. Namely, they are able to operate the industrial engine in the SFC bucket all the time with inlet fogging. An aero engine already operates outside the SFC bucket during takeoff (designed for cruise conditions) so fogging inlet wouldn't have much effect on efficiency.

Aero-derivative Applications

Currently, many industrial gas turbine inlets are being fogged for peak power and emissions reductions. A combustor water injection system is an option for the LM-2500 industrial and marine applications. At this time, the systems are known to function well yet data on the specifics of fuel consumption, emissions reductions and overhaul cycle are not forthcoming. The reasons for this reluctance to release these data are unclear.

SUMMARY

Water is an excellent source of cooling and power control. Water injection at specific locations can enhance performance of gas turbine systems. In industrial applications, fogging gas turbine inlets or direct injection of water into gas turbine combustors, decreases NOx and increases power.

Experiments with water injected trapped vortex combustors (TVC) demonstrate reductions in NO_x by factors up to three in a natural gas fueled (TVC) and up to two in a liquid JP-8 fueled (TVC) over a range in water/fuel and fuel/air ratios.

Industrial data relating the economic and environmental benefits and detriments of water injected turbomachines are sorely needed as are studies needed to determine suitability for airlines applications.

APPENDIX
Experimental TVC-Combustion System

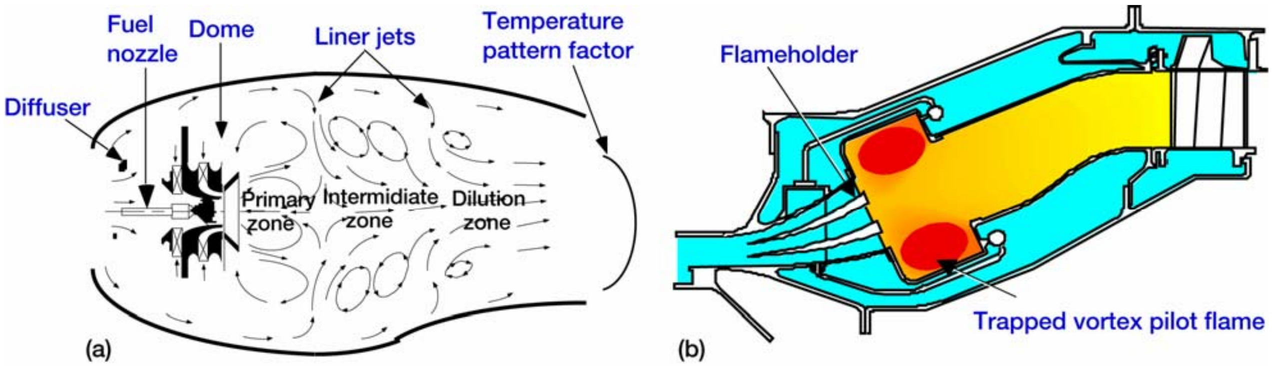
The Trapped Vortex Combustor (TVC) was conceived at AFRL in the early 1990's and has undergone several stages of development. It departs from the conventional combustor system in several very specific ways (a) the combustor provides the opportunities to be a one or two stage system, primary combustion takes place in the cavity with the secondary burning zone taking place along the dome face, where the cavities interact with the main air flow system, where additional fuel can be injected to augment the primary or cavity burning zone (b) the diffusion zone is stabilized by low pressure zones between the injectors that both drafts the cavities and mixes the mains (c) ignition is initiated within the cavities (d) mixing is highly three dimensional within a tight zone of combustion. The physical characteristics also depart significantly from those of a conventional burner as can be seen by comparing figures A1(a) and (b). The conventional combustor consists of several components as the fuel lines, nozzles, swirlers, and liners of sufficient length to achieve mixing and a reasonable pattern factor. Usually there are four zones, diffuser, primary, intermediate mixing and dilution, figure A1(a). While the TVC has some of these features, it is a much shorter combustor system with fuel and air injection at specific locations both in the main diffuser and the cavities, figure A1(b). In either system the goal is high efficiency (> 99 percent), low emissions (reductions > 50 percent ICAO standards), all at low weight and cost with robust stable operations for thousands of hours of operation.

The original proof of concept test configuration is shown as figure A2(a), where a pintle type configuration confined a vertical pattern with stable combustion. Further developments were realized and evaluated in the work supported by contractors and shown in figure A2(b). This system represented a significant advance in burner stability and fueling modes. The visible flame structure attested to the short stable burner. Subsequent research investigated the effects of fueling and air injection on mixing and combustor performance (fig. A2(c)). The success of the fueling studies lead to the construction of the sector rig, figure A2(d), similar to the one used for reporting the data herein, to continue combustor studies over a wide range in φ, turn-down ratios, altitude relight etc. In all cases the TVC was stable with high combustion efficiency within the normal operating range. The axisymmetric TVC configuration tested at DOE-NETL-Morgantown, WV, differs from the sector combustor in that a diffuser-baffle is used and the fuel is natural gas. Some flow patterns are also illustrated, figure A2(e).

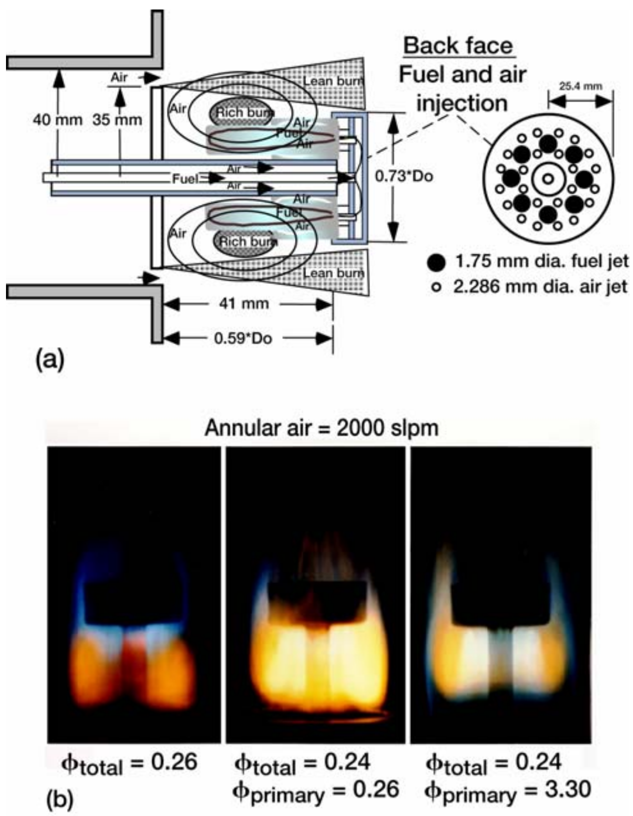
In a parallel experimental facility, a lobed mixer high speed TVC concept was tested at AFRL, figure A3(a). Inlet air could be heated or not and accelerated to M = 1 at lobe exit plane. The mixing and combustion took place within the zone adjacent to the lobe exit and within the cavity, figure A3(b). While CFD, figure A3(c), has shown adequate benefits and tests have confirmed reasonable efficiencies, two major problems remain (a) how to adequately mix out the core and (b) what is the free-flight stagnation pressure loss. Slot mixing benefits have also been computed as shown in the work of Waitz and Underwood, figure A3(d).

The high pressure combustor facility which housed the high speed lobed TVC is illustrated in figures A4(a) and (b). Air is supplied from a central compression and heating facility and ducted into the facility. The horseshoe loop is the back-side cooling air supply that does not enter into the combustion process and the doughnut ring is cavity air supply. The main and cavity fuel manifolds are the horizontal tubes with multiple lines attached, just above the main flow path. Not readily seen are instrumentation and emissions probe sample lines. The system ran stable over a large range in φ, turn-down ratios, and pressure drops to over 50 percent achieving M > 1 at the lobe mixing exit plane.

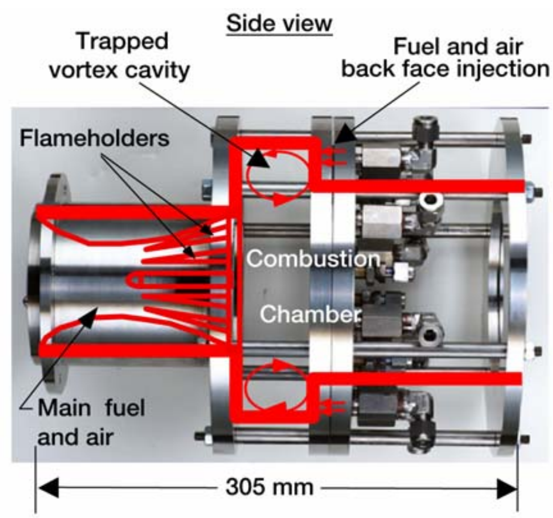
Emissions probes were mounted on stings with lines snaked out through the exhaust diffuser section. These measurements are critical to evaluating both the particular gas emissions and the efficiency of the combustor. For example, at normal operating conditions the CO is quite low, see figures 2 and 5 of the text. Note that as water or steam is injected into the flow, the CO bucket (point where CO is a minimum) begins to shift toward higher equivalence ratios. In figure 2, for a NETL-side piloted can-combustor, this shift is from φ = 0.4 to 0.65. And why is this significant? It represents stability of the combustor. Combustor stability is decreased as one shifts to high equivalence ratios. However, note the difference between the NETL-TVC combustor and the NETL-LECTR (HAT cycle) combustor illustrated in figure 5. The equivalence ratio φ for the TVC is shifted very little between baseline and 10 percent steam while the HAT cycle φ shifts from 0.41 to 0.57. These shifts corroborate known stability results for the TVC combustors.



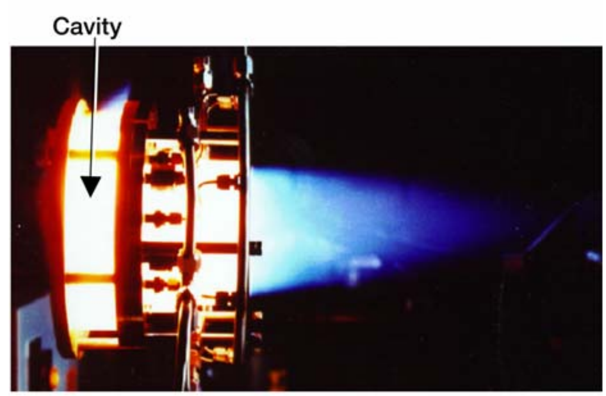
A1.—Combustor systems. (a) Conventional combustor. (b) Trapped vortex combustor.



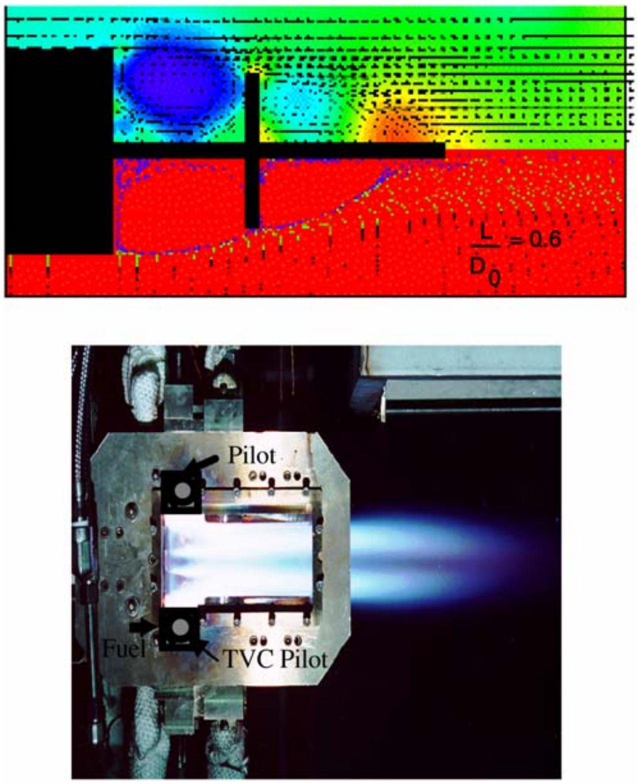
A2.—(a) First generation trapped vortex combustor with (b) flame photographs at different flow conditions.



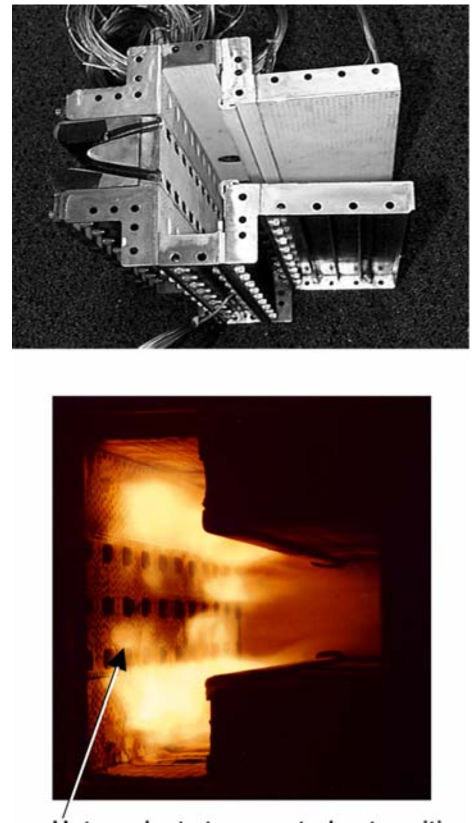
Side view of second generation trapped vortex can combustor.



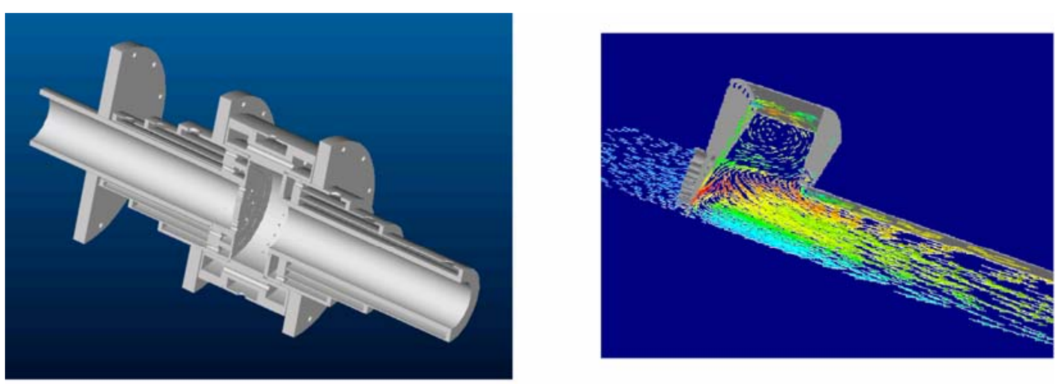
A2.—(b) Side view of flame in second generation TVC can at equivalence ratio of 1.



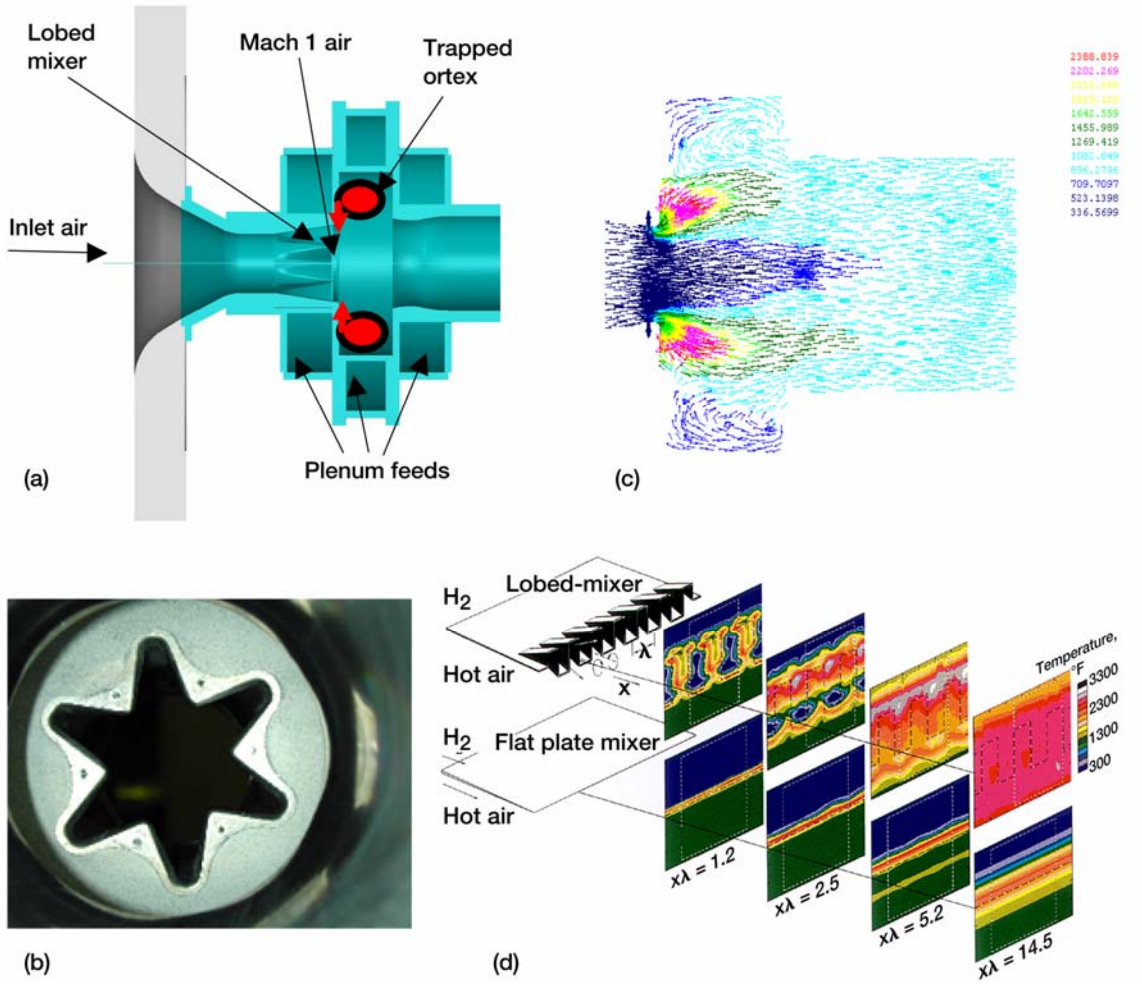
A2.—(c) Illustration and side photographs of third generation trapped vortex combustor.



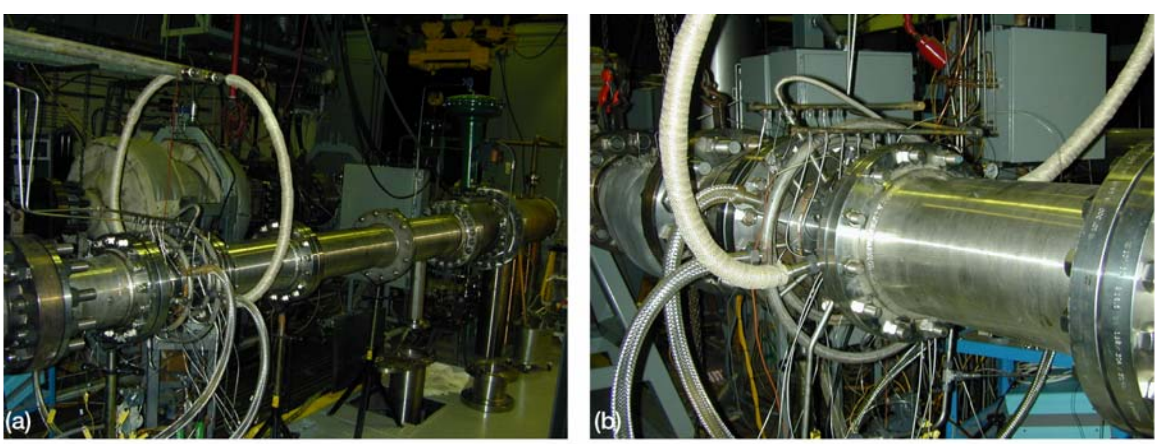
A2.—(d) High-pressure, tri-pass diffuser, and double vortex (2P-2V) TVC.



A2.—(e) TVC development tests including DOE-NEIL concept.



A3.—Lobed-mixer developmet. (a) High-speed lobed mixer LM/TVC. (b) Photo. (c) NASA calculated temperature field M = 1 Inlet velocity. (d) Lobed mixer consumes reactants 3-10-times faster. Ref: Waitz and Underwood, AIAA paper 95-2471, 1995.



A4.—High-pressure combustion research facility. (a) Forward view (flow goes left to right). (b) Aft view.

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From antiquity, water has been a source of cooling, lubrication, and power for energy transfer devices. More recent applications in gas turbines demonstrate an added facet, emissions control. Fogging gas turbine inlets or direct injection of water into gas turbine combustors, decreases NO_x and increases power. Herein we demonstrate that injection of water into the air upstream of the combustor reduces NO_x by factors up to three in a natural gas fueled Trapped Vortex Combustor (TVC) and up to two in a liquid JP-8 fueled (TVC) for a range in water/fuel and fuel/air ratios.

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